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Nitrogen Fertilization and Cropping System Impacts on Soil Quality in Midwestern Mollisols

A. E. Russell,* D. A. Laird, and A. P. Mallarino

ABSTRACT

High grain production of corn (*Zea mays* L.) can be maintained by adding inorganic N fertilizer, and also by using crop rotations that include alfalfa (*Medicago sativa* L.), but the relative impact of these management practices on soil quality is uncertain. We examined the effects on soil of N fertilization rate (0, 90, 180, 270 kg ha^{-1}, corn phase only) in four cropping systems: CC, continuous corn; CS, corn–soybean [*Glycine max* (L.) Merr.]; CCOA, corn–corn–oat (*Avena sativa* L.)–alfalfa; and corn–oat–alfalfa–alfalfa (COAA). The 23- and 48-yr-old experimental sites, situated in northeast (Nashua) and north central (Kanawha) Iowa, were in a replicated split-plot design and managed with conventional tillage. At Nashua, we measured available N, potential net N mineralization and microbial biomass C (MBC) throughout the growing season; all were significantly higher in the CCOA system. At both sites, post-harvest N stocks, and soil organic C (SOC) concentrations were significantly higher in systems containing alfalfa. Grain yield was most strongly correlated with soil N properties. At Nashua, N fertilizer additions resulted in significantly lower soil pH (0- to 15-cm depth) and lower exchangeable Ca, Mg, and K and cation exchange capacity (CEC) in the CC and CCOA systems. In an undisturbed prairie reference site for Nashua, low available N, low pH, and high CEC suggested a strong influence of the vegetation on nutrient cycling. In terms of management of soil fertility, inclusion of alfalfa in the rotation differed fundamentally from addition of N fertilizer because high yield was maintained with fewer adverse effects on soil quality.

Conventional management practices can differ significantly in their impacts on soil C sequestration (Studdert and Echeverría, 2000; West and Post, 2002; Russell et al., 2005). These differences in C sequestration are expected to have broad implications for long-term soil fertility, soil quality, and the impact of management on the surrounding environment. Soil C quantity and quality influence the capacity of soil to store nutrients, and to release nutrients for crop growth during decomposition and mineralization (Lal, 2002; Horwath et al., 2002). Soil organic C influences water quality by regulating the release of nutrients to the ground water (Lal et al., 2004), and air quality by regulating emissions of greenhouse gases such as CO_2 and N_2O to the atmosphere (IPCC, 1997).

Although soil productivity can be enhanced both through N fertilization and by growing legumes in rotation, the two management strategies may have different impacts on nutrient cycling and soil quality. Nevertheless, both can increase available N (Ta et al., 1986; Liebig et al., 2002; Mayer et al., 2003), and thereby increase yields. An important advantage of using symbiotic N-fixing crops in the context of a complex cropping system is that it increases the diversity of substrates available for N mineralization, and thereby promotes a more sustainable N supply (Sanchez et al., 2001). Legumes can also provide improved soil structure, erosion protection, and greater biological diversity (Jensen and Hauggaard-Nielsen, 2003).

Achieving the optimal N addition, to maximize yield while minimizing environmental impact, is an important goal of best management practices. Excess N additions can negatively influence soil properties. For example, long-term N fertilization has been demonstrated to decrease levels of exchangeable Ca, Mg, and K, and cation exchange capacity (CEC) (Barak et al., 1997; Liu et al., 1997), and the reversibility of these changes is unknown. Ammoniacal fertilizers also cause acidification of soil (Bouman et al., 1995; Barak et al., 1997; Liebig and Doran, 1999; Gajda et al., 2000), but the rate of acidification depends on the crop system (Liebig et al., 2002) and soil type. Recent research has highlighted the adverse impact of excessive N fertilizer use in agricultural land on aquatic ecosystems (Turner and Rabalais, 2003). Furthermore, N fertilization may contribute to production of greenhouse gases such as N_2O (Robertson et al., 2000). For cropping systems using biological N fixation, N losses via volatilization, N_2O emission, and NO_3 leaching may be lower during precropping and cropping, but post-harvest losses may be greater relative to cropping systems that rely on N fertilization (Jensen and Hauggaard-Nielsen, 2003).

Effects of management on soil properties are difficult to evaluate because spatial and temporal variability in soil properties can easily mask the impact of management. We utilized two well-managed, replicated, and long-term experiments in northern Iowa to address the effects of N fertilization and cropping system on indices of soil quality. We have previously reported soil properties that related to C sequestration for these sites, including soil C stocks, potential mineralization of C (PMC), particulate organic C (POC), and resistant C (Russell et al., 2005). In this study, our objectives were to quantify the effect of N fertilization and cropping systems on bulk density (ρ_b), available N, potential net N mineralization (PMN), MBC, SOC concentrations, exchangeable cations, CEC, and pH.

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Abbreviations: CC, continuous corn; CCOA, corn–corn–oats–alfalfa; CEC, cation exchange capacity; COAA, corn-oats-alfalfa-alfalfa; CS, corn-soy; MBC, microbial biomass C; MSD, minimum significant difference by Tukey's multiple comparison test; POC, particulate organic C; SOC, soil organic C; ρ_b, bulk density.

MATERIALS AND METHODS

Site Descriptions

This study was conducted at two long-term sites, Nashua and Kanawha, located within the Iowa State University Northeast and Northern Research and Demonstration Farms, respectively, described by Russell et al. (2005). To summarize, each site contains an experiment in a split-plot randomized block design, with cropping system as the main plot, and subplots consisting of four N treatments, 0, 90, 180, and 270 kg ha^{-1}, hereafter referred to as 0-N, 90-N, 180-N, and 270-N. The Nashua experiment, in effect since 1979, contains three blocks. The Kanawha plots, in two blocks, were established in 1954. Three cropping systems were sampled at Nashua, CC (for grain), CS, and CCOA. A fourth system (not available at Nashua) was sampled at Kanawha, COAA. Thus, we sampled a total of 36 plots at Nashua and 32 plots at Kanawha. At Nashua, the size of the subplot was 4.6 by 15.2 m, and at Kanawha, 6.1 by 12.2 m. The design contains all phases of each rotation in every year; we sampled only the first corn phase of each rotation at both sites. Of these treatments, the CS system with 90- or 180-N is most typical for the Midwestern U.S. region. Within the states of Illinois, Iowa, Minnesota, Missouri and Wisconsin, 2.1 billion kg of N fertilizer are applied per year to crops; with N application on 97 to 100% of all farms, the average annual rate per farm is 135 kg ha^{-1} within the region (USDA-National Agricultural Statistics Service, 1997a). In this region, 25.6 million ha, or 79% of cropland is in CS rotation (USDA-National Agricultural Statistics Service, 1997b). Hayden Prairie, a native prairie, served as a reference site for Nashua. This prairie is situated 50 km north of Nashua, on similar soil series. The two most dominant species are Kentucky bluegrass (*Poa pratensis* L.) and big bluestem (*Andropogon gerardii* Vitman) (Russell et al., 2005). A similarly undisturbed reference site no longer exists for Kanawha.

Nashua soils were Kenyon (fine-loamy, mixed, mesic superactive Typic Hapludolls) and Readlyn (fine-loamy, mixed superactive mesic Aquic Hapludolls) loams formed in reworked till sediment, with mean particle-size distributions of 319, 456, and 224 g kg^{-1} sand, silt, clay, respectively. Kanawha soil was a Webster clay loam (fine-loamy, mixed superactive mesic Typic Endoaquolls) formed in till-derived sediments, with mean particle-size distributions of 219, 449, and 332 g kg^{-1} sand, silt, clay, respectively (Robinson et al., 1996). The Nashua site is 120 km east of Kanawha. Mean annual precipitation over a 53-yr period ending in 2004 was 806 mm at Kanawha, 847 mm at Nashua, and 845 mm at Hayden Prairie (Iowa Environmental Mesonet, 2004). All cropping systems were tile-drained and rain-fed. At Nashua, chisel plowing (to a depth of 23–25 cm) in the fall following corn and alfalfa was the primary tillage, whereas Kanawha was moldboard plowed to a depth of 25 cm. Spring disking was secondary tillage for plots that had been plowed the previous fall and the only tillage used for plots with soybean residues at both sites. The depth of disking was 10 to 13 cm at Nashua and 8 to 10 cm at Kanawha. There was no other tillage. Nitrogen fertilizer treatments were applied as granulated urea in the corn phase of the rotation, in the spring immediately before disking, and thus incorporated with disking. At Kanawha, to keep pace with modern rates of N fertilization, the rates had been increased (except for the 0-N) in 1971 and 1984, as described by Russell et al. (2005); the current N fertilization rates have been in effect since 1984. From 1979 onward granulated urea has been applied at Kanawha; before 1979, granulated 34–0-0 or 33–0-0 was applied.

Published crop grain yields include means from 1979 to 1998 for Nashua (Mallarino and Pecinovsky, 1999) and from 1985 to 1998 for Kanawha (Mallarino and Rueber, 1999). The following corn grain yields are summarized to correspond with increasing N fertilization, the 0-, 90-, 180-, and 270-N fertilization treatments. In the CC system, yield increased with N fertilization: 3.48, 6.48, 8.00, and 8.49 Mg ha^{-1} at Nashua; and 3.35, 6.79, 8.41, and 9.16 Mg ha^{-1} at Kanawha. In the CS system, the soy phase apparently supplied N, as the increase in corn yield was not as great: 6.28, 8.82, 9.29, and 9.47 Mg ha^{-1} at Nashua, and 6.25, 8.71, 9.85, and 10.15 Mg ha^{-1} at Kanawha. Even more N is apparently supplied in the CCOA system, with first rotation corn yields of: 7.63, 9.02, 9.38, and 9.48 Mg ha^{-1} at Nashua and 9.10, 9.62, 9.80, and 9.92 Mg ha^{-1} at Kanawha. Yields in the COAA system (Kanawha only) were 9.62, 9.57, 10.05, and 9.76 Mg ha^{-1}.

Sampling Protocol

During an intensive study conducted only at Nashua in 2001, soil was sampled at monthly intervals from April to November for a single depth interval, 0 to15 cm, in the CC, CS, and CCOA plots, in the 0 and 180 kg ha^{-1} N treatments only. In this intensive study, we measured available N and potential net N mineralization (NO_3– plus NH_4–N for both), MBC, and gravimetric soil moisture for the 0- to 15-cm depth, and soil temperature at 4 cm.

In an extensive study, conducted at both Nashua and Kanawha in 2002, soil was sampled one time, in all cropping systems (corn phase only) and under all four N levels. We sampled in October, post-harvest but before fall tillage because results from our intensive study indicated that variability in soil N concentrations and bulk density was relatively low at this stage in the growing season. The prairie was sampled in late August 2002. We measured pH (in water and KCl), bulk density, and total SOC, soil inorganic C, and total N for each of six depth increments, 0 to 5, 5 to 15, 15 to 30, 30 to 50, 50 to 75, and 75 to 100 cm, to follow the protocols of a multi-site project. Soil C stocks to 1 m are reported by Russell et al. (2005). Exchangeable cations (Ca, Mg, and K), and CEC were measured only for the 5- to 15-cm depth interval. Because these soils were moldboard- and chisel-plowed, the top 15 cm was well homogenized; preliminary data indicated that the 0- to 15- and 5- to 15-cm layers did not differ significantly.

Laboratory Evaluations and Calculations

Potential net N mineralization was determined as the difference between "final" and "initial" quantities of inorganic N in fresh soil samples incubated at 23°C for 28 d. Extractions for "initial," also referred to as "available" N, were conducted on samples that were kept on ice until extraction within 4 h of collection. For available N and potential net N mineralization, 10 g of soil were extracted with 2 *M* KCl using a 1:5 soil/solution ratio. The soil solution was shaken for 30 min, allowed to settle for 30 min, and then filtered through No. 42 Whatman paper. Two blanks were also extracted at every sample time to account for contaminant nitrate and ammonium in the filters and vials, but these values were below the detection level. The filtrate was analyzed colorimetrically for NO_3–N and NH_4–N using an automated ion analyzer (QuickChem 4100, Lachat Instruments Division, Zellweger Analytics, Inc., Milwaukee, WI).

Microbial biomass C was measured by fumigation and direct extraction with 0.5 *M* K_2SO_4 on duplicate 8-mm sieved 50-g field-moist samples that had been stored at 4°C until processing within 7 d after sampling (Tate et al., 1988; Rice et al., 1996). Duplicates were run for both fumigated and nonfumigated subsamples. Organic C in the fumigated and nonfumigated extracts was measured using a Phoenix 8000 carbon analyzer (Tekmar-Dohrmann, Cincinnati, OH) calibrated with potassium phthalate standards. Biomass C was calculated using the correction factor (k = 0.33) of Sparling and West (1988).

Exchangeable Ca, Mg, Na, and K were determined by displacement with 1 M ammonium acetate (pH 7) and subsequent measurement by atomic absorption spectrometry for Ca and Mg and emission spectroscopy K and Na. Cation exchange capacity was determined by summation of exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) (Sumner and Miller, 1996; Warncke and Brown, 1998). Soil pH was measured using a stirred slurry of 10 g air-dried soil in 10 mL of deionized water and a separate 10-g soil sample in 10 mL of KCl (1 M) (Thomas, 1996).

Total soil C and N concentrations were determined by dry combustion using a Carlo-Erba NA1500 NSC elemental analyzer (Haake Buchler Instruments, Paterson, NJ). Total SOC concentration was calculated as the difference between total soil C and soil inorganic C, which was measured by the modified pressure-calcimeter method (Sherrod et al., 2002). Soil N storage was calculated as the product of ρ_b, soil thickness, and N concentration, as described by Russell et al. (2005). Bulk density was determined for each depth increment by the soil core method (Blake and Hartge, 1986).

Statistical Analyses

This experiment had a split-plot randomized block design, with a main treatment of cropping system, and subtreatment of N fertilizer addition. All effects were treated as fixed (PROC GLM, Littell et al., 1991). We tested for homogeneity of variances and normality of distributions. Available N and potential net N mineralization had unequal variances; analyses were performed on natural-log transformed data that did fit the assumptions. A repeated measures ANOVA design was used to test for differences among the monthly sampling times for available N, potential net N mineralization, and MBC (Littell et al., 1991). We evaluated multiple comparisons using Tukey's studentized (HSD) range test. Planned contrasts within a cropping system consisted of cropping systems with and without alfalfa in the rotation at Kanawha (CC and CS vs. CCOA and COAA). Relationships between yield and various soil properties were assessed using Pearson correlation analysis. We used PROC REG to test for linear relationships between N fertilizer addition and soil pH (SAS Institute, 1990).

RESULTS AND DISCUSSION

Nitrogen Availability and Soil Quality

At the Nashua site, available N varied significantly over the course of the growing season ($P < 0.0001$), and the pattern over time differed among N-fertilizer treatments and cropping systems ($P < 0.004$, repeated measures analysis)(Fig. 1). Not surprisingly, following fertilizer application in April, available N was higher in the fertilized plots from May to September. Available N was generally higher in the CCOA cropping system relative to the CC or CS systems throughout the growing season. Early in the season (May and June), this trend was significant ($P < 0.05$) in the unfertilized treatments. In June, and September-November, the trend was significant in the fertilized treatment. In our reference site of native undisturbed prairie, relatively low available N concentrations of 1.6 mg kg^{-1} in August 2002 (5–15 cm) indicated a low potential for N losses via leaching in the undisturbed prairie, relative to the fertilized cropping systems.

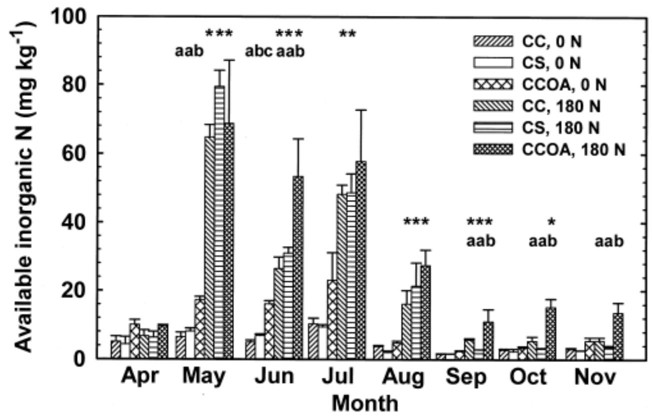

Fig. 1. Available inorganic N (0–15 cm) at the Nashua, IA long-term experimental site. Means (± 1 SE) in 2001 varied by month in interaction with cropping system and N fertilization. Within each month and N treatment, significant differences among cropping systems are denoted by different letters (Tukey's test, P = 0.05). Within each month and cropping system, significant effects of N fertilization are denoted by an asterisk above the 180 kg N ha^{-1} bar (P < 0.05). All undesignated cropping system and fertilization effects are not significant.

Potential net N mineralization varied significantly over the course of the growing season ($P < 0.0001$)(Fig. 2), but the trend did not differ with N fertilization regime ($P = 0.29$). The variation over time did differ among cropping systems ($P = 0.059$; all in corn phase), perhaps owing to the fact that the previous crop was different in each system. As with available N, potential net N mineralization also tended to increase with CC = CS < CCOA ($P = 0.009$, repeated measures analysis). The results indicate that potential net N mineralization was strongly influenced by the previous crop's detritus, rather than the current crop or rate of N fertilization. We hypothesize that the peak in May under all treatments was the result of optimum soil moisture and temperature conditions (Fig. 3) for mineralization of detritus from the previous crop. The treatments may well differ in their effects on N mineralization, but given inherently high variability in this soil process, it is difficult to detect significant differences among treatments. Deng and Tabatabai (2000) also measured potential net N mineralization in these sites; although the foci and methods for their study differed from this study, where sampling overlapped, results were similar for the two studies.

Microbial biomass C differed over the growing season ($P < 0.0001$), but not in interaction with N fertilization ($P = 0.27$) or cropping system ($P = 0.10$) (Fig. 3). Thus, cropping system consistently influenced microbial biomass ($P = 0.001$, repeated measures analysis), with CS < CC ≪ CCOA. The effect of N fertilization was not significant ($P = 0.45$). With data for only 1 yr, we cannot determine the generality of these observed seasonal trends. However, over all plots and sampling times at Nashua (n = 143), potential net N mineralization was significantly correlated with post-harvest SOC concentration ($P = 0.02$) (Table 1), but not with microbial biomass, soil moisture or POC (reported by Russell et al., 2005). Microbial biomass cannot necessarily be equated with microbial activity, but our trends among cropping

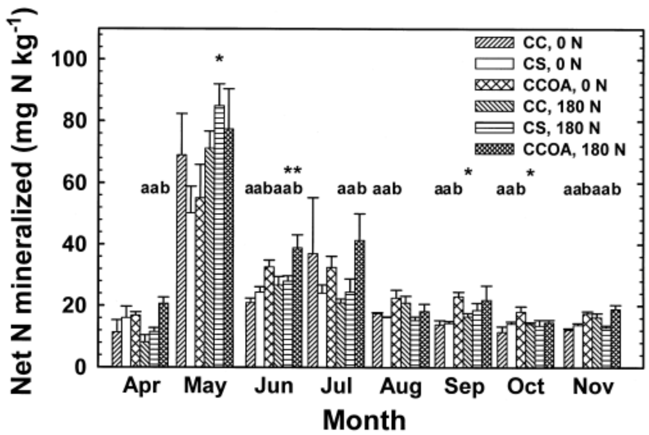

Fig. 2. Potential net N mineralization at the Nashua, IA long-term experimental site. Means (± 1 SE) in 2001 varied by month in interaction with cropping system and N fertilization. Within each month and N treatment, significant differences among cropping systems are denoted by different letters (Tukey's test, P = 0.05). Within each month and cropping system, differences between N fertilization treatments are denoted by an asterisk above the 180 kg N ha^{-1} bar (P < 0.05). All undesignated cropping system and fertilization effects are not significant.

Table 1. Long-term effects of cropping system and N fertilization on soil organic C, 0- to 15-cm depth, at the Nashua, and Kanawha, IA long-term experimental sites.

Cropping system†	N treatment, kg N ha^{-1}‡ 0	90	180	270	Mean	MSD§	P
	g C kg^{-1}						
			Nashua				
CS	18.3 a¶	19.8	19.1	20.0 a	19.3	3.2	0.32
CC	20.4 ab, A	22.0 AB	22.4 B	23.0 b, B	21.9	1.9	0.02
CCOA	22.7 b	22.6	22.4	23.6 b	22.9	2.3	0.37
MSD	3.2	3.7	4.0	2.8			
P	0.02	0.12	0.07	0.02			
			Kanawha				
CS	30.7	30.9	32.0	29.3	30.7	19.2	0.92
CC	28.3	30.9	34.3	31.9	31.3	16.2	0.47
CCOA	37.7	33.8	36.2	37.1	36.2	10.9	0.45
COAA	33.3	38.8	35.7	37.3	36.3	15.8	0.49
MSD	14.9	24.0	8.6	13.8			
P	0.17	0.49	0.26	0.15			
Pcc#	0.05	0.02	0.11	0.02			

† C = corn, S = soybean, O = oats, A = alfalfa. All plots were sampled in the corn phase.
‡ N fertilizer added in corn phase only.
§ MSD = minimum significant difference, Tukey's test, P = 0.05.
¶ Values within a column (N rate) followed by the same lowercase do not differ significantly between cropping systems (P = 0.05). Values within a row (cropping system) followed by the same uppercase letters do not differ significantly between N treatments ($P \leq 0.05$).
# Pcc = Significance ($P > F$) of planned contrast between cropping systems with and without alfalfa in the rotation (CC and CS vs. CCOA and COAA).

systems and N fertilizer additions reflected the trends in urease activity described by Klose and Tabatabai (2000) and phosphatases described by Dodor and Tabatabai (2003). In our study, cropping system significantly influenced other indices of soil quality such as SOC concentration, which was significantly higher in systems that contained alfalfa (both sites, Table 1), and bulk density, which was significantly lower in systems with alfalfa (both sites) (Table 2). Soil C in the prairie was 66.1 g kg^{-1}, 2.8 times higher than the highest values in the cropping system, and thus explained the low bulk density.

Exchangeable Cations, Cation Exchange Capacity, and pH

At both sites, CEC (5–15 cm) was significantly lowest at the highest N fertilization levels (Fig. 4). Decline in exchangeable Ca with N fertilization followed a similar trend (Fig. 4). At Nashua, exchangeable Mg also declined significantly with N fertilization (P = 0.002); mean (SE) values across cropping systems were 333 (9), 325 (11), 302 (6), and 283 (8) mg kg^{-1} at N fertilization rates of 0, 90, 180, and 270 kg ha^{-1}, respectively. At Kanawha, the effect of N fertilization on exchangeable Mg was not significant. Exchangeable K was significantly influenced by N fertilization, with exchangeable K lowest at the 180-N fertilization rate at both sites (Fig. 4). The effect of cropping system was significant across all N treatments only for exchangeable K (P = 0.025 at Nashua; P = 0.072 at Kanawha); respective means (SE) for CC, CS, and CCOA were 141 (4), 115 (5), and 122 (3) at Nashua and 262 (14), 235 (16), 210 (11), and 217 (12), COAA at Kanawha. Less removal of K by corn grain relative to other crops, especially alfalfa, is the most likely explanation for the effect. The only other effect of cropping system was that at Nashua, although CEC and exchangeable Ca declined with N fertilization in the CC and CCOA systems, this did not occur in the CS system. We suggest that these results are complex because leaching, and increased crop removal due to N fertilization and/or the specific nutrient demands of the crops in the sequence all play a role in the base status of soils in this study. Exchangeable Ca and Mg in the reference prairie soil, 3997 and 617 mg kg^{-1} respectively, were 157 and 183% higher than the highest values for the agricultural plots, despite the fact that the Nashua soils had received uniform lime applications in 1981 (14.2 Mg ha^{-1}) and again in 1989 (6.1 Mg ha^{-1}). The Ca/Mg ratio of the lime is not known, but high Ca/Mg ratio would account for the apparent greater depletion of Mg from the agricultural soils than Ca relative to the prairie soil. Addition of N fertilizer had a less obvious effect on exchangeable K, yet in the CC cropping system at both sites, exchangeable K tended to be

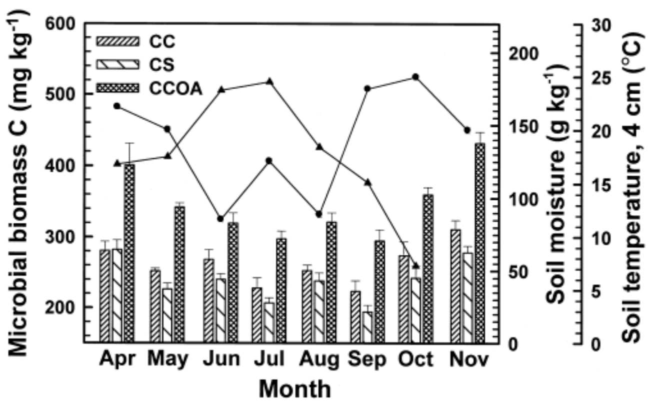

Fig. 3. Microbial biomass C at the Nashua, IA long-term experimental site. Means (± 1 SE, across N fertilization treatments) that differ among cropping systems are denoted by different letters (Tukey's test, P = 0.05). Soil moisture (●) and soil temperature (▲) are means over all treatments.

Table 2. Significant differences among cropping systems in bulk density at the Nashua and Kanawha, IA long-term experimental sites.

Site	Depth	Cropping system†				Prairie	MSD‡	*P*
		CS	CC	CCOA	COAA			
	cm	Mg m^{-3}§						
Nashua	0–5	1.09 a¶	1.02 ab	0.95 b	–	0.22	0.13	0.04
	5–15	1.25 a	1.23 a	1.17 b	–	0.49	0.05	0.01
Kanawha	0–5	0.96 ab	1.01 a	0.87 b	0.88 ab	–	0.14	0.04
	5–15	1.06 ab	1.07 a	1.01 bc	0.99 c	–	0.06	0.02
	15–30	1.18 a	1.12 ab	1.08 b	1.07 b	–	0.09	0.03

† C = corn, S = soybean, O = oats, A = alfalfa.
‡ MSD = minimum significant difference by Tukey's test.
§ Data are post-harvest, October 2002, except prairie data are from August, 2002.
¶ Values within rows (among cropping systems) followed by the same lowercase letter do not differ significantly ($P = 0.05$). Native prairie was not included in the ANOVA's.

higher in the unfertilized relative to the fertilized treatments. The effect, significant only at Nashua, probably reflects less removal of K by cropping, due to lower yields and/or less leaching of K from unfertilized plots. Over the years, the plots have periodically received uniform rates of K fertilization. However, at the time of sampling no K fertilizer had been applied for 9 yr at Nashua and at least 7 yr at Kanawha.

At both Nashua and Kanawha, soil pH did not differ significantly among cropping systems at any depth. In contrast, pH declined linearly with N addition in the 0- to 5- and 5- to 15-cm depths ($P < 0.0001$). In this 0- to 15-cm layer, pH decreased from 5.9 to 5.6 at Nashua, whereas the decline at Kanawha was from 5.7 to 5.6 (0- and 270-N treatments, respectively). At Nashua, this effect of N fertilization on pH was significant to a depth of 75 cm: pH decreased from 6.0 to 5.7 (15–30 cm, $P = 0.004$); from 5.8 to 5.5 (30–50 cm. $P = 0.002$); and from 5.7 to 5.4 (50–75 cm, $P = 0.004$) (90 and 270 N, respectively). Owing to a history of liming, the decline in pH was relatively small, as found also by Moore et al. (2000) in their 1996–1997 sampling at these sites. Soil acidification is a common legacy of the long-term use of high rates of ammoniacal fertilizers, and accelerated weathering of clay minerals due to acidification has been shown to reduce soil CEC values (Barak et al., 1997; Pernes-Debuyser and Tessier, 2004). At Nashua, the effect of N fertilization on CEC differed among cropping systems: in the CC and CCOA systems, respective CEC was 10 and 13% lower in the 270-N, relative to the unfertilized treatment, while N fertilization had no significant effect on CEC in the CS system (Fig. 4). Values for CEC in the reference prairie soil were much larger (162%) than the highest values for any of the agricultural soils. Acidification alone cannot account for the large decrease in CEC, hence the cause of the CEC decline is not clear. The prairie soil had a pH value of 5.72 near the surface (0–5 cm) that decreased with depth to 4.26 for the (50- to 75-cm depth). This may reflect redistribution of bases in the prairie soil by the vegetation. At Kanawha, weathering of calcareous rocks in the sediments may buffer effects of N fertilization.

Long-Term Soil Fertility

We further evaluated the effects of management practices on soil fertility and quality by evaluating relationships between published long-term corn yield averages for these sites (first crop of the rotation) and soil properties measured in 2001–2002, Years 22 through 23 and 47 through 48 of the experiments at Nashua and Kanawha, respectively. Yield was most strongly correlated with soil N properties; significantly so with total N (Fig. 5), and available N and potential net N mineralization in June (Table 3).

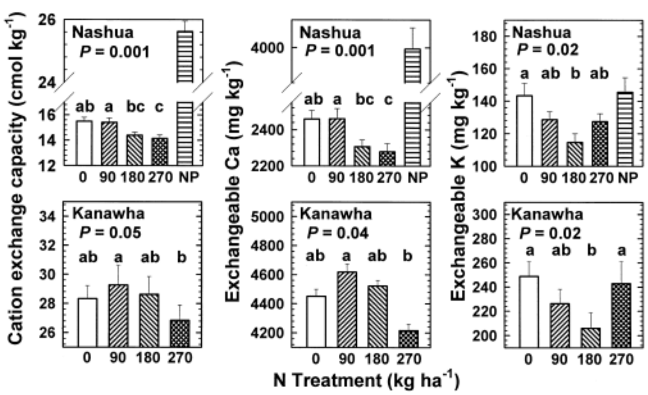

Fig. 4. Cation exchange capacity and exchangeable Ca and K at the Nashua and Kanawha, IA long-term experimental sites. Values are means (± 1 SE) across cropping systems. Differences among N treatments are denoted by different letters (Tukey's test, $P = 0.05$). 'NP' refers to the native prairie reference site, not included in the ANOVA.

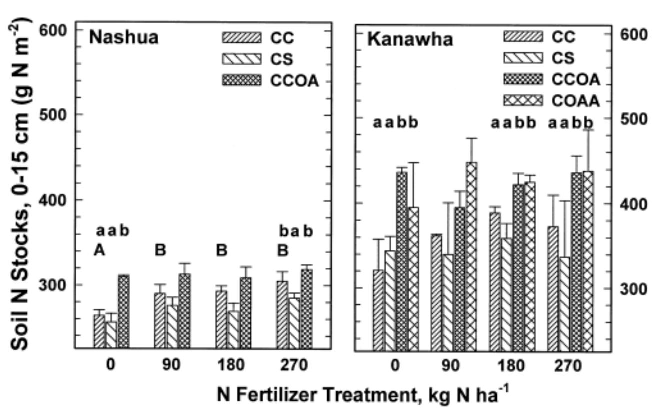

Fig. 5. Total soil N stocks (0–15 cm) at the Nashua and Kanawha, IA long-term experimental sites. Means (± 1 SE) that differ among cropping systems are denoted by different lowercase letters and among N treatments by uppercase letters (Tukey's test, $P = 0.05$).

Table 3. Correlations of corn grain yield with soil properties at the Nashua and Kanawha, IA long-term experimental sites.

Variable	Site†	N‡	r	P
C mineralization§, Oct	Kanawha	16	0.24	0.38
	Nashua	12	−0.11	0.44
Microbial biomass	Nashua	6	0.38	0.45
Total soil N	Kanawha	16	0.64	0.01
	Nashua	12	0.52	0.08
Available N	Nashua	6	0.82	0.04
N mineralization§, June	Nashua	6	0.76	0.08
Bulk density	Kanawha	16	−0.26	0.33
	Nashua	12	−0.23	0.47
Cation exchange capacity	Kanawha	16	−0.22	0.42
	Nashua	12	−0.37	0.24
pH	Kanawha	16	−0.55	0.03
	Nashua	12	−0.42	0.17

† Data for Kanawha, and Nashua ($N = 12$ only) are for the 5- to 15-cm depth, 2002. Data for Nashua ($N = 6$ only) are from 2001, 0- to 15-cm depth.
‡ Each datum for each of the analyses was the mean of 2 blocks at Kanawha and 3 blocks at Nashua.
§ Potential net mineralization values from laboratory incubations.

It is clear that N fertilization can provide adequate N for crop production. The data presented in this study suggest however, that crop rotations that include alfalfa generally have a more consistent and positive impact on potential net N mineralization and available N than addition of N-fertilizer at 180 kg N ha^{-1}. Long-term corn-yield averages for these plots (Mallarino and Pecinovsky, 1999; Mallarino and Rueber, 1999) mirror our N availability trends, with yield averages indicating a strong response to N-fertilization for the CC system and moderate responses in the CS system. For the second year of corn in the CCOA system, yields show a small response to N fertilization, and no response for first year of corn in the CCOA and COAA systems. Baldock et al. (1981) found that the increase in corn yield following legumes can be attributed to the N that they supply, but also to other unknown factors unrelated to N limitation. In our study, available N was significantly higher in the COAA system in May and June; perhaps the timing of N release from decomposing alfalfa influenced crop yield more than would be predicted from the quantity of N added to the system. Gil and Fick (2001) also found that total net N mineralized was high under alfalfa, and they attributed this to the lower C/N ratio of its biomass. Because the effect of tillage is confounded with cropping system, however, the positive effects on soil quality in the CCOA system cannot be attributed with certainty to the effects of alfalfa alone.

Long-term yield was negatively correlated with pH, significantly so at Kanawha. In terms of management effects on soil pH, cropping system differed fundamentally from N fertilization in that high yields could be maintained in systems that included alfalfa without addition of N fertilizer and the associated decline in pH and CEC. Liebig et al. (2002) also found that soil pH was unaffected by cropping system alone.

In summary, in the Midwestern U.S. region where 79% of cropland is in a single system, CS, and 97 to 100% of corn fields receive an average rate of 135 kg $ha^{-1}yr^{-1}$ fertilizer N, these results from long-term experiments indicated that the type of cropping system had a greater positive effect on soil quality than did N fertilization. Whereas N fertilization increased only one measure of soil quality in one system, SOC in the CC system, cropping systems that contained alfalfa influenced three measures of soil quality: bulk density, SOC, and MBC. The CS and CC had the lowest soil quality by these measures. In general, although N fertilization was associated with an increase in available N, it was also correlated with a decline in soil quality, as evidenced by a decline in pH, CEC, and exchangeable cations; and an increased need for fertilizers to maintain yields, especially at Nashua, which is situated on reworked tills. In contrast, high available N, high N stocks, and high yields in the unfertilized systems that contained alfalfa indicated that symbiotic N fixation supplied sufficient N to sustain yields, and did so without negative effects on soil quality.

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